Civil Aviation Research and Development

An Assessment of Federal Government Involvement

FLIGHT VEHICLES AND AIRBREATHING PROPULSION

A report by the ASEB Ad Hoc Committee
Flight Vehicles and Airbreathing Propulsion

AERONAUTICS AND SPACE ENGINEERING BOARD
NATIONAL ACADEMY OF ENGINEERING

CIVIL AVIATION RESEARCH AND DEVELOPMENT

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AIRBREATHING PROPULSION

AERONAUTICS AND SPACE ENGINEERING BOARD
NATIONAL ACADEMY OF ENGINEERING
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Foreword

The National Academy of Engineering established the Aeronautics and Space Engineering Board (ASEB) in May 1967 to advise the National Aeronautics and Space Administration (NASA) and other government agencies. In consultation with officials of NASA, the Department of Transportation, the Federal Aviation Administration, the President's Science Adviser, certain interested committees of Congress, and the National Aeronautics and Space Council, as well as other government and private groups, the Board selected as its first topic of study, "Civil Aviation Research and Development: An Assessment of Federal Government Involvement." The Board's report under that title was published on August 13, 1968. It summarizes reports of six ad hoc committees, including this report by the Committee on Flight Vehicles and Airbreathing Propulsion.

As background information for the reader of the committee reports, the most important conclusions and recommendations of the Board are stated below (summary report, pages v-vi).

> The Board has concluded that in a favorable economic climate civil aviation can continue to fluorish; in fact it can accelerate its beneficial growth if a carefully conceived program of planning and research and development aimed specifically at the civil air transport system is carried out.
>
> After considering the multiplicity of factors affecting the growth of civil aviation, the Board concluded that the three most critical factors are (1) airport and support facilities, (2) noise, and (3) air traffic control.
>
> The most important recommendation of the Board pertains to knitting together more tightly the civil aviation research and development activities of the Department of Transportation, its

major operating unit, the Federal Aviation Administration, and the National Aeronautics and Space Administration, and especially to dividing their responsibilities according to capability. The DOT should provide the leadership in conducting systems studies to identify, analyze, and rank civil aviation goals as well as the research and development needed to attain these goals; NASA should be responsible for research and development in all the areas of importance to civil aeronautics; the FAA should, in addition to operating the airways network, be responsible for the systems testing of the resulting operational concepts and hardware.

The Board's report also contained many detailed technical recommendations concerning research and development needed to ensure the continued growth of civil aviation. These pertain to most of the important areas of civil aviation, including systems and specific areas of flight vehicles, aircraft operations, air traffic control, airport and support facilities, economics, and noise.

The Board assigned detailed work to six ad hoc committees covering the above specific areas. Each committee was composed of knowledgeable men from different parts of the aviation community; their valuable contributions are sincerely appreciated by the Board.

Board membership is listed in Appendix I. The Board wishes to express its appreciation and indebtedness to a large number of individuals beyond its membership with whom it conferred. These are also listed in Appendix I. The Board is indebted to the American Institute of Aeronautics and Astronautics, the American Society of Civil Engineers, the American Society of Mechanical Engineers, the Institute of Electrical and Electronics Engineers, and the Society of Automotive Engineers for conducting special studies, making available special reports, and identifying members for participation in an advisory capacity. The cooperation of these societies served to broaden the advisory base.

The Board is particularly grateful for the valuable assistance provided by the members of the Ad Hoc Committee on Flight Vehicles and Airbreathing Propulsion, who are listed on the following pages.

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Introduction

Organization for Conduct of the Flight Vehicles and Airbreathing Propulsion Study

The members of the Committee on Flight Vehicles and Airbreathing Propulsion were selected to bring to the study all aspects of the field. The co-chairmen, members of the ASEB, brought to the committee their experience in the fields of research and development, manufacturing, and operations of aircraft and engines. Advisers were included from the field of aerodynamics, safety, control systems, corporate and private aircraft design and manufacturing, V/STOL and helicopter design and manufacturing, and propulsion research and development.

Method of Conducting the Study

In preparing this report, the co-chairmen drew upon the advice and counsel of the members and advisers and on the suggestions offered by a number of other individuals in the aeronautics field. Their views were consolidated into this single report for presentation to the ASEB, but in the process of editing and consolidation an effort was made to retain the essence of each of the contributions. After review at a meeting in Seattle, Washington, on March 27-29, 1968, the report was reviewed again by members. Finally, reports submitted by special panels of the AIAA were studied to determine if there were additional suggested areas that would require research and development efforts.

In several cases, the information received included comments and recommendations relating to matters other than the technology of vehicles and propulsion, such as operating problems and support facilities. Although these comments and recommendations are included in this report,

emphasis has been placed on the vehicle, its propulsion, and their subsystems.*

Background

During the early phases of the ASEB study, the discussions by experts in the various fields of civil aviation and review of Senate Document No. 90, "Policy Planning for Aeronautical Research and Development," prepared by the staff of the Library of Congress, identified major problems that are either already restricting the growth of civil aviation or that are expected to limit growth of aviation in the future. Among the problems cited were congestion of airways and airports with related traffic control difficulties, safety, aircraft noise, and sonic boom associated with supersonic flight. Although attention has been given to these problems, they still remain a potential retarding influence on the growth of civil aviation.

Scope of the Study

This survey of flight vehicles and airbreathing propulsion problems should be read with the recognition that other ad hoc committees were active in the following areas:

Aircraft operations
Air traffic control
Airport and support facilities
Economics of civil aviation
Noise

After a short discussion of overall transportation problems the report covers separately the flight vehicle and the propulsion system. The major areas considered in the section on flight vehicles are vehicle control, aerodynamics, mechanical systems, structures, and the V/STOL and helicopter system development. In the section on the propulsion system,

*In a number of areas that the committee has suggested for increased research and development emphasis, NASA has already initiated a program or is in the process of increasing the level of activity. Even so, the committee has chosen to include in its report all of these recommendations.

the major areas considered are engine combustor research and compressor technology, installed performance of propulsion systems, instrumentation and controls for propulsion systems, and fuels.

In discussing the role of the government in civil aeronautical research and development, comment has been made on each of the areas considered, but in so doing, the intent has been to be consistent with the following overall classification of research and development activities that may properly be undertaken by government agencies.

1. Applied research that exceeds the resources of private industry but that serves as a stimulant to the industry and provides a source of fundamental information. The traditional role of the original National Advisory Committee for Aeronautics (NACA) was to conduct this type of effort. The NACA work was heavily oriented toward aerodynamic research and was conducted at a time when very few privately owned wind tunnels existed in the country. In the last twenty years, large private aerodynamic staffs and test facilities have been developed. Privately owned test facilities are now important elements in a manufacturer's competitive posture. Although aerodynamic research remains to be done, a rejuvenation of aeronautical activities within NASA would place greater emphasis on other areas. These other areas should include automatic flight control, materials, structural criteria and advanced structural concepts, and propulsion systems including noise attenuation.

Such an expansion of NASA aeronautical activity would of course require an increased budget. However, the proportion of the NASA budget devoted to aeronautics would be small compared to that assigned to space activities. Although relatively small, this part of NASA activity is vital to the national interest and should receive top NASA management attention and support. It should be recognized as primarily a research activity and should not include total system management functions such as are now incorporated in the NASA space organization. The existence of these management functions and their sheer size may tend to draw both management and public attention away from the aeronautics research program; thus it may require special attention to organization and staffing on the aeronautics side to maintain an effective balance.

2. Major development programs where private economic resources and/or motivation are inadequate to achieve national objectives (e.g., the SST program). The desire for government agencies to engage in applied research to promote and stimulate aviation appears reasonably straightforward. The question of the extent to which the government should undertake the management of civil aviation development is much more complex. It has frequently been suggested that NASA should manage the development of civil aviation systems in the same manner that they now manage the development of space systems. Such an approach should be adopted, however, only when the programs clearly exceed the resources of private industry. The most obvious future requirement for such government action appears to be in the development of an integrated airway-airport system that accounts for both domestic and international constraints. The DOT may be a more logical government management agency than NASA for this case, with NASA involved in the supporting research and development.

Expansion of government management to all new civil aviation product development has been suggested. The government-managed "proof-of-concept" approach may be desirable to explore developments of questionable practicability such as nuclear-powered airplanes, hypersonic airplanes, and laminar flow control. However, the government should carefully avoid developments that have sufficient economic motivation to generate competitive private development. Such private developments have given the United States a steadily widening lead over foreign competitors, whose product development decisions are made by government agencies, often with a competitive performance and time lag resulting in a lack of acceptance in the international market.

3. Programs associated with public welfare. The government must play the primary role in establishing regulations that affect the welfare of the public, such as noise, pollution, and safety. The industry should complement this effort by supplying the government with information that allows technical and economic considerations to be properly assessed. Government regulations and specifications have a powerful effect on design concepts and ultimate hardware. Those regulations that control takeoff, landing, flying qualities, etc., in such a way as to affect the economics of operation should

be based upon sensitivity studies to determine the influence of the variables involved. There is at times a concern in industry that the government may be unable to conduct adequate studies of the impact of its regulations, with the possibility that compliance with regulations may unnecessarily compromise the performance and/or economics of the air transport system.

4. Programs that require interaction between government agencies. Many future research and development programs will require coordination among various government agencies. For instance, the proper balance among noise restriction, land purchase, and airline fare structures is a problem of enormous complexity that can be resolved only with participating activity among interrelated government agencies. The development of the airway and airport systems mentioned previously also falls into this category, requiring the interaction of many government agencies.

Even with the above categories in mind, identification of the specific government agency to be involved is not always obvious. Although the committee has suggested agencies that it considered appropriate to carry out or participate in the recommended research and development, in its summary report the Aeronautics and Space Engineering Board generally chose to omit any such references. Thus the agencies concerned are given the options of determining appropriate implementing activities.

Discussion of

Problems and Recommendations

It is the view of the committee that since the vehicle and its propulsion are operating in an overall transportation system environment, a statement of principal overall system problems should be made as a background for suggestions in specific areas of research and development.

GENERAL CONSIDERATIONS

On a system basis, the following problem areas seem to be the most pressing. These problems, if not effectively attacked, could severely constrain the orderly growth of air transport:

1. The individual capacities of airways and air traffic control, airports, and ground transportation in relation to growing traffic volume.
2. The capacity of the overall system to handle the concurrent growths of scheduled air transport and general aviation.
3. The need for improved technology in all areas of civil aviation in order to provide more efficient transportation at both short and long ranges.
4. The impact of noise and air pollution on the public versus the economic impact of arbitrary regulations on air transport economics and growth.
5. The development of air transportation to provide efficient transport of cargo throughout the total system.
6. The development of the total air transport system to better serve each local community as well as each regional community.

TECHNICAL CONSIDERATIONS

This section of the report is divided into two major groups, the flight vehicle and the propulsion system. For the convenience of the reader not concerned with the whole technical field, the subareas of the above groups each include a discussion of the principal problems, the state of the art, the research and development needed, and the suggested government role. With the background outlined under "General Considerations" and the qualifications in mind as previously stated in the Introduction, "Scope of the Study," concerning the classification of government activity in research and development, the committee offers the following comments and suggestions in those areas of research and development considered to be important to the continued growth and economic health of the United States air transport system.

The Flight Vehicle: Vehicle Control

Automatic Flight Path Control

1. Principal Problem. Rapidly increasing air traffic is causing terminal airspace congestion that results in holding delays, excessive ground-controller and flight-crew work load, and increasing likelihood of midair collisions. Automatic flight path control and traffic control systems, as well as blind-landing systems, lack the precision necessary to provide positive control of traffic and effective space allocation. The present system fails to provide for balanced use of airspace capacity and terminal capacity.

2. State of the Art. Automatic landing systems have been certificated for Category II weather conditions. These systems are typically dual redundant and, in the event of failure, revert to a manual control mode with the airplane in a trim condition. Navigational aids are used separately rather than as part of an integrated system. Current overland radio-navigation aids, such as VOR/DME,* provide navigation accuracies of 2 to 4 degrees in bearing and about 600 ft in distance measurement. The inertial navigation systems, which are about to enter commercial service,

*Very high frequency omnidirectional range/distance measuring equipment.

will provide a position accuracy of 2 to 10 miles after several hours of operation without updating or calibration. This inertial accuracy is essentially the state of the art for long overwater flights.

3. Research and Development. The national air traffic control system is designed to sequence aircraft on standard patterns within defined arrival and departure corridors in the terminal area and to provide for clearance on point-to-point patterns en route. There are, however, many airborne equipment possibilities that are complementary to air traffic control. Such equipment could provide more precise adherence to an assigned pattern and schedule plan, thus allowing increased traffic density with improved safety, reduced holding delay, and less demand on traffic controllers and flight crews.

Navigation accuracy that would alleviate the problems previously discussed is about ±300 ft en route, ±100 ft in the terminal area, and approximately 25 ft relative to the runway centerline at touchdown in a blind-landing situation. Navigation systems that employ radio-navigation aids, inertial equipment, and an airborne digital computer to improve accuracy by combining and filtering iteratively sampled data can provide the required precision. The computer in the system can easily provide the means for storage of preprogrammed flight plans, which, with the precise navigation, is the key to automatic path guidance. However, laboratory development of prototype combined systems and flight test are required.

Blind landing in Category III weather conditions requires the development of a fail-operative automatic control system that should probably be triply redundant and must include suitable equalization or mid-value voting logic and failure warning devices. Laboratory simulations of such systems indicate that it is timely to design and flight-test prototype hardware. It is likely that the instrument landing system (ILS) currently installed at most major airports will be useful for several more years, but eventually a more reliable, flexible, and accurate replacement will be required to achieve optimum runway operations rates under all weather conditions.

In the area of combined navigation, control, and display systems, the military has supported the early developments. Recently, several flight control system and instrument suppliers have begun commercial equipment development and at

least two major aircraft manufacturers have undertaken systems research and development. Cockpit instrumentation making use of the cathode-ray tube is under development and many prototype laboratory models of these instruments exist. When contrast and reliability problems are solved, these devices will be satisfactory for cockpit display requirements of the future.

Even with very precise navigation for controlled traffic there is a need in the total system for pilot warning indicators (PWI) and collision avoidance equipment. One corporation recently developed a cooperative collision warning system to reduce risks in their flight-test operations, but it is complex and depends on accurate time synchronization, and both the air and ground hardware components seem to be too expensive to obtain general acceptance. A recent meeting of the FAA-sponsored Collision Prevention Advisory Group revealed that agreement is yet to be reached on PWI requirements and that new technical solutions are required. Industry attendees were urged to intensify their research efforts.

Recommendation:

Develop improved flight vehicle capabilities that will alleviate the problem, such as:

a. Precision navigation and automatic path guidance.
b. Fail-operative blind landing.
c. Accurate display of the navigation and guidance situation.
d. A PWI and/or collision avoidance system.

To summarize needs in airborne equipment, additional development is required for integrated navigation and control systems employing more sophisticated airborne computers, multiple navigation sensors, more comprehensive display equipment, and fail-operative controls.

4. Suggested Government Role. The government role performed by the DOT and the CAB in certification, evaluation, and coordination of research and development efforts should continue. The DOT should also be encouraged to accelerate planning, definition, and implementation of air traffic control developments that complement improved aircraft. Within this framework the avionic and airframe industries can be depended upon to continue development of equipment to reduce control problems, and the airlines will test promising items in the operational environment.

The inertial navigation industry has military experience to offer and has expressed an interest in participating in the commercial applications. These agencies appear to have the capability to undertake these tasks. The major aircraft manufacturers should take the lead in the overall system research and development activity.

Electronic Flight Control

1. Principal Problems. Large airplanes operating at high altitudes and at high Mach number require stability augmentation systems and lightweight low-friction flight control command subsystems with high reliability and fail safety. To minimize structural damage or failure during flight in extreme turbulence will require active suppression of structural modes of vibration by control surface action.

2. State of the Art. For airplanes presently being designed and for those projected over the next decade, control systems that employ a purely mechanical link between the pilot's controls and the airplane's surfaces are impractical. Current design philosophy is to provide electronic control systems with sufficient redundancy to operate the airplane but with mechanical standby systems. The decision to put complete reliance on an all-electronic system has been adopted in some isolated areas such as throttle and engine inlet controls where sufficient redundancy exists, but no designs are being implemented that incorporate all-electronic flight control systems without a mechanical reversion system at least in the commercial airplane field.

The Anglo-French Concorde utilizes an all-electronic primary control system with position-sensors connected to the column and wheel that provide adequate command responses and damping characteristics in all axes. This airplane has a mechanical standby system that is considered to be required for safety of flight. The SST will use a similar scheme for the primary control, incorporating a triplex fail-operational system, using electronic components and a backup mechanical system. The electronic and mechanical interfaces that are used in a system of this nature are not completely developed at this time, but they are based upon the experience gained in such programs as the F-111. Model suppression techniques are being investigated on the B-52, the B-70, and the SST.

3. Research and Development. Before all-electronic systems are acceptable for commercial aircraft as the only means of control (without mechanical standby systems), several years of operational experience on military or commercial programs will be required. Some operational experience on the use of all-electronic control for supersonic airplanes has been obtained from the F-111, but the total number of flight-test hours does not approach that required to gain overall acceptance of this type of system. At the present time the principal efforts in the United States are those conducted by the Air Force Flight Dynamics Laboratory and by the Army as part of its advanced helicopter development program.

Recommendation:

Conduct additional research in support of development, testing, and demonstration of reliability and safety for all-electronic systems of flight control.

4. Suggested Government Role. Experience in operation of such systems can be gained from a combination of flight experience on military airplanes and the SST prototype. Needed are increased emphasis on research and development within the Air Force Flight Dynamics Laboratory and increasing involvement of NASA in adaptation of such systems to civilian uses.

Design for Rough Air Penetration

1. Principal Problem. To improve the safety of existing and future transports in rough air.

2. State of the Art. Pilot operational procedures and techniques have been defined that have led to safer manual control in rough air. In addition, autopilot modes have been proposed and developed on new transports for use in rough air.

3. Research and Development. Rough air penetration continues to be a problem for large high-performance aircraft. Structural integrity standards have been improved through the years so that there has been great progress toward elimination of structural failures of airplanes as a result of direct encounter with rough air. The rough air structural problems of commercial aircraft have resulted primarily from upsets in which unusual speeds and altitudes were produced and failures occurred when the pilot attempted to right the airplane.

Spectral (indicating distribution of turbulence wavelengths) turbulence models are being defined and proposed for structural design purposes. To cover the control design aspects over the full range of interest, more needs to be known in the turbulence wavelength range of 1,000 to 50,000 ft. There has been some work in the United Kingdom toward development of spectral techniques for solution of control problems. Some appraisal has been made of past significant airplane incidents in turbulence, and a number of industry efforts are involved with development of airborne turbulence detectors. Nevertheless, further research and development is needed.

Recommendation:

a. Improve the definition of atmospheric turbulence models for use as design criteria.

b. Develop spectral techniques applicable to control problems, as well as to load problems in rough air. Distribution of turbulence wavelengths and intensities are involved in solution to these problems.

c. Appraise past significant airplane incidents in turbulence.

d. Develop on-board clear-air turbulence detectors.

4. Suggested Government Role. The government role is twofold: to support increased air transport safety and to define suitable design criteria. NASA should continue its own studies, and integrate with other studies (e.g., those done by the Air Force and the National Severe Storms Laboratory), to produce atmospheric design data and criteria covering the whole wavelength range of interest. Such data are essential to enable designs of the airplane and control system to cope with the rough air environment. This approach could lead to the determination of control powers and other airplane characteristics based on rough air criteria rather than on past experience.

The Flight Vehicle: Aerodynamics

Aerodynamic Wing Development

1. Principal Problem. Improvement is needed in the design of lighter-weight subsonic wings.

2. State of the Art. Two-dimensional airfoils are designed theoretically and wind-tunnel-tested. Promising

sections are integrated into three-dimensional wings by experimental and quasi-theoretical procedures. Successful wings require wind-tunnel tests to optimize the three-dimensional tailoring.

3. Research and Development. Improved aerodynamic efficiency is required throughout the full speed range of future aircraft. Emphasis is needed on research and development leading to lighter-weight subsonic wings through the use of thicker sections for the same critical Mach number and through improved three-dimensional tailoring. Work is needed in analytical airfoil design and experimental airfoil evaluation.

Recommendation:

a. In analytical airfoil design, develop a theoretical method of airfoil design that will produce airfoil shapes with superior drag level and drag rise characteristics. This includes the establishment of design criteria and the development of computer methods that can handle supercritical flow conditions.

b. In experimental airfoil evaluation, initiate specific wind-tunnel testing to develop these airfoils, investigate effects of Reynolds number, determine low-speed leading edge modification required, and substantiate the design methods.

4. Suggested Government Role. NASA should support work on the applied research problems described above. Industry also should be concerned with these problems but, in addition, should develop special airfoils needed to meet individual requirements.

Laminar Flow Control (LFC)

1. Principal Problem. A successful means is needed to permit the practical application of boundary layer control (BLC) to increase aerodynamic cruise efficiency.

2. State of the Art. The Northrop X-28* program provided the majority of basic information necessary for a prototype LFC transport. Flight results demonstrated:

a. Full chord laminar flow to a Reynolds number of 47×10^6.

*Two Douglas NB66-D aircraft were modified by Northrop for the Air Force to investigate design, manufacturing, operation, and maintenance problems of laminar flow control for drag reduction.

b. Elimination of the leading edge contamination problem through chordwise suction (i.e., increased $\underline{R}_\theta$ from 90 to 250).

3. Research and Development. There are a number of additional programs needed prior to the design of a competitive LFC transport:

a. Integration of a high-lift system (leading and trailing edge devices) with LFC to allow operation from relatively short fields.

b. Evaluation of the effect of wing-mounted engines on the ability to maintain laminar flow (i.e., minimize isobar distortion).

c. Development of a method of construction that would permit visual inspection of a primary structure and would allow the use of integral fuel tanks.

d. Investigation of LFC wings having good transonic flow.

e. Continued refinement of the details of slot and duct flow to avoid both internal and external disturbances.

f. Additional development of means for controlling the effects of surface roughness, disturbances, gaps, etc.

g. A thorough understanding of the economics of an LFC airplane including such items as the cost of manufacturing and installation of this system as well as the required maintenance and operational reliability. This information is required to determine whether the LFC airplane is competitive with current and future turbulent-flow aircraft.

These programs are not being undertaken because the X-21 LFC program was cancelled. The DOD support has been stopped because no suitable mission has been defined that requires LFC.

Subsequently, one airplane was destroyed and the other parked on the Edwards AFB bombing range. The program was terminated without obtaining the maintenance and operational reliability information that was one of the program's fundamental objectives.

Recommendation:

Attempt practical demonstrations of boundary layer flow control to increase aerodynamic cruise efficiency.

4. Suggested Government Role. If the second X-21 has not been destroyed, the government should retain it until its possible future use can be decided. Further, support should be provided for an applied research program to answer the remaining questions.

Integrated Aerodynamics and Propulsion Systems

1. Principal Problem. There is a need for a more intimate combination of the propulsion and aerodynamic systems to provide improved high-lift capability and cruise performance.

2. State of the Art. Current subsonic aircraft research and design practice tends to treat aerodynamic and propulsion technical problems as separate entities. For instance, analysis of the propulsion inlet and exhaust are separated from that of the aerodynamic surfaces. Therefore, there is a minimum of consideration given to interaction between the propulsion and aerodynamic components. Mutually beneficial interference is unlikely to occur under these circumstances; indeed interference can be detrimental.

3. Research and Development. The two aspects of the problem - namely, takeoff and landing performance and cruising performance - are treated separately.

Takeoff and Landing Performance

The field length requirements of a transport, i.e., whether or not the airplane can meet STOL performance requirements, determines to a large extent the degree to which a propulsion system can be combined with the aerodynamic features of a configuration. Demand bleed systems for BLC, thrust rotation at lift-off, and automatic asymmetric thrust control systems for use in the event of propulsion system malfunction are typical of needed developments in the field of thrust vectoring during takeoff and climbout.

Landing requirements center on converting the energy potential of the propulsion system to the development of lift for minimum flight speeds. Such methods can involve high-lift boundary layer control, thrust vectoring, or any other means that will provide lower approach speeds with more precise flight path control.

Recommendation:

a. Initiate research and development aimed at realizing a more intimate combination of propulsion and aerodynamic systems to provide high-lift capability for takeoff and landing.

b. Continue development of an accurate and efficient means for thrust vectoring during takeoff and climbout and for converting the energy potential of the propulsion system to lift at minimum flight speeds.

Cruising Performance

It is increasingly desirable that airplane propulsion and aerodynamic features be integrated to provide improved cruise performance. Some work is being done to make better use of propulsion for takeoff and landing performance, but very little is being accomplished toward increasing cruise performance.

Recommendation:

Attempt to integrate airplane propulsion and aerodynamic features to provide improved cruise performance by minimizing interference or producing favorable interference, regenerating retarded boundary layer air, or developing a new propulsion concept that would distribute the propulsion force in some optimum manner over the aerodynamic surfaces.

4. Suggested Government Role. Because of its wide applicability, much of the basic technology for interactive propulsion and aerodynamics could be accomplished by NASA. However, in most cases the compromises must be the responsibility of industry as they are highly configuration-dependent. All degrees of interaction are required, from VTOL through long-range cruise airplanes. A significant contribution could be made by providing basic technology across the spectrum of these requirements.

The Flight Vehicle: Mechanical Systems

1. Principal Problem. The committee noted that as commercial airplanes increase in size and performance, the contribution of equipment systems to airplane reliability and economics becomes increasingly important. This importance is demonstrated by increased interest and activity in crash safety and in new concepts such as on-condition maintenance and on-board maintenance computers. Entirely new approaches and major improvements for equipment systems may be desirable to keep pace with other developments.

2. State of the Art. Equipment systems have not advanced by significant increments in recent years; instead they have evolved slowly by a series of relatively minor refinements. Today's equipment systems have been designed mostly with yesterday's state of the art. Their total importance in airplane safety has demanded conservative, proven designs.

Many system components are developed and produced by a large number of small specialty companies. Many of these companies do not have the resources to finance major equipment innovations. Airframe companies, on the other hand, have been reluctant to commit required resources beyond the major investment required for basic aircraft and engine development. These conditions have tended to produce a climate of conservatism that has impeded system concept innovation.

Prior to this country's entry into space activities, an innovative forcing function was provided by the military services, in particular the Air Force. Under this stimulation, such basic system concepts as constant speed drives, hydraulic-powered flight control, and air cycle refrigeration were developed. Progress since then has not been at a pace consistent with achievements in propulsion, aerodynamics, structures, and electronics.

3. Research and Development. Not enough is being done by equipment manufacturers because of lack of resources. Airframe companies can and are doing some of the required research, but demands for solutions of today's equipment problems make it difficult to set aside sufficient resources to make the large gains required for future airplanes.

Recommendation:

a. Continue development of predictive-failure techniques. In addition, consideration should be given to establishing a means for collection and statistical analysis of maintenance and failure data to stimulate system concept changes and improvements in equipment design.

b. Study system concepts from an overall airplane standpoint. Integration of air conditioning, auxiliary power units, secondary power, engine starting, and powered lift systems offer appreciable gains in overall airplane simplicity for a given level of performance.

c. Develop basic system design criteria using a statistical base. Most equipment systems are designed for the worst case expected in service, even though the worst occurs very infrequently. A sounder statistical knowledge of requirements would allow design on the basis of the conditions most likely to be encountered, with the further provision that unusual types of failure would be handled by overload or reserve equipment. This could result in

lower-weight smaller-capacity systems and could remove those constraints that prevent consideration of advanced concepts.

d. Develop methods to analyze mechanical equipment systems by dynamic-transient analyses in order to improve reliability and maintainability and to reduce weight. Most systems are designed to steady-state criteria, then examined for the transient case. For example, the landing gear, brakes, and tires are subjected to severe transient conditions, and the dynamic behavior of these components mutually influence each other, the airplane structure, and the runway.

e. Increase research and development in the field of fluidics for application to airplane controls. Because of inherent simplicity and lack of a signal conversion interface, fluidics offers substantial improvements in reliability and maintainability. Although a great deal of research is being devoted to fluidics technology, increased effort might accelerate application to control systems.

4. Suggested Government Role. A stimulating contribution could be made by the government through initiating and funding research projects as indicated above. Such projects should include involvement of airframe companies, airlines, and equipment suppliers. NASA would appear to be the agency with the technical skills and research facilities to initiate the necessary equipment research. Government, in cooperation with industry, should establish the means for data collection and analysis of maintenance and failure data.

The Flight Vehicle: Structures

Structural Stiffness

1. Principal Problem. Improvements in aerodynamic efficiency, use of high-strength materials, and increases in airplane size are producing structures with reduced stiffness and an attendant increase in aeroelastic deflections and dynamic load response. This can result in increased loads, more difficult control problems, and decreased ride comfort.

2. State of the Art. Unless added stiffness is necessary to preclude flutter, present practice is to design for strength and accept the resulting structural stiffness.

3. Research and Development. Rather than continue to design for strength and use automatic control inputs to reduce loads or to improve ride and handling qualities, it may be more efficient to design using stiffer materials. However, both approaches should be and are being pursued by industry. Both NASA Langley Research Center and NASA Lewis Research Center are conducting research on advanced composites; emphasis at NASA-Lewis is on high-temperature engine components. In addition, the Air Force Materials Laboratory is conducting research on advanced composites and beryllium in conjunction with industry.

Recommendation:

Increase the effort to develop materials with higher ratios of modulus of elasticity to density to assist designers in solving the severe problem of achieving adequate structural stiffness.

4. Suggested Government Role. Government agencies should continue to sponsor the advanced composites effort and should accelerate it where possible. However, more industry participation is recommended, including further development of high-strength high-stiffness fibers and matrix materials. Industry has the capability to develop structures using advanced composites to increase stiffness and to conduct trade-off studies to compare these new techniques with the present practice of handling the flexibility problem.

Flutter

1. Principal Problem. Flutter analyses do not adequately account for wing-body interaction effects and control surface aerodynamics, especially in the transonic region. Better understanding of these phenomena is essential in the development of safe structures.

2. State of the Art. Present flutter analysis methods are satisfactory for major airplane components for both subsonic and supersonic conditions, but the aerodynamic influence of the control surfaces and the effects of wing-body interference are not understood.

3. Research and Development. Both industry and government are engaged in research on this problem, but virtually no work is being done for the transonic region.

Recommendation:

a. Develop flutter analyses that account for wing-body interaction effects and control surface aerodynamics, especially in the transonic region.

b. Initiate research to establish the theory, and verify by experiment using both model and full-scale structures.

c. Collect and evaluate data, and develop an overall program to carry out the research.

4. Suggested Government Role. NASA should take the lead in this effort, and should gather existing data and form a government-industry committee to evaluate data and design an overall program to accomplish the objectives.

Structural Implications of Human Factors

1. Principal Problem. Generally, pilot effects are ignored in estimating design loads, but the pilot can have a significant effect on structural loads, especially during emergency conditions.

2. State of the Art. The current practice is to include only the effects of autopilots, stability augmentation systems, and control displacement rates in the dynamic analysis, because the system can thus be represented mathematically.

3. Research and Development. Some human-factors simulation work is underway, but little attention has been given to the effect of pilot response on design loads.

Recommendation:

Develop a working model to provide criteria for pilot behavior under emergency conditions, because piloting technique can have a substantial effect on structural loads, especially during such conditions. These criteria could then be related to the pilot-automatic control interface. Much of this work can be accomplished with moving-base simulators.

4. Suggested Government Role. The work should be handled by NASA, including both government and industry human-factors experts.

Structural Materials

1. Principal Problem. For the past thirty years or so, aluminum has been the basic material employed in aircraft structures, with a fairly modest use of other materials.

However, new materials show great promise in reducing structural weight. Accelerating the incorporation of these new materials in the next generation of commercial airplanes is a difficult problem.

2. State of the Art. The current practice provides for careful selection and use of materials in structures where their particular mechanical·characteristics are best suited. Most materials used in today's aircraft structures, when compared on a strength-to-density basis, fall into rather narrow bands such that major weight reductions are not possible by changing materials alone. These materials continue to be used because of the vast experience and confidence in their use.

3. Research and Development. A limited amount of work in all of these areas is being done by industry, government agencies, universities, and research institutes. Research institutes, for example, with industry and government guidance, should conduct the basic materials research. Continued support should be provided by the government for the production of high-strength filament materials to promote their use and reduce their costs. Private industry should translate the results into practical structure and obtain manufacturing and service experience.

Recommendation:

a. Initiate the research and development needed to demonstrate that structures can be made for production from these new materials that will perform satisfactorily in service. Some specific problems that must be resolved in addition to providing adequate strength are fatigue performance, brittleness, creep, fracture toughness, resistance to corrosion, and stiffness. Fabrication problems are cleaning and bonding, machining and forming, welding and diffusion bonding, and manufacturing of high-strength filament structures.

b. Place increased emphasis on basic studies of matrix systems, both metal and polymers, to ensure long-term environmental and microstructural stability. Surface and electrochemical properties must be related to interfacial reactions and kinetics. Fatigue, creep, and fracture mechanisms must be studied in terms of the material's microstructural characteristics.

4. Suggested Government Role. An agency of the government, such as NASA, should be designated as a focal point for this basic material research. The Air Force Materials

Laboratory has been instrumental in the special area of development and application of boron filaments. It should continue in this role and serve as the focal point for advanced composites application and concurrent development of inspection and repair techniques.

Fatigue and Fail Safety

A manufacturer of civil transport airplanes must supply products that are safe, provide ease of maintenance, and have public appeal and earning capability. Thus, the airplane must sustain flight loads, ground handling, and all other normal environmental factors without significant loss of structural integrity throughout its lifetime.

In order to ensure sustained structural integrity, the manufacturer must design the airplane to be fatigue resistant. This requires a quantitative understanding of how fatigue cracks originate and how fast they are likely to grow. In general, a policy of fail-safe design is followed so that in the event of structural failure of an important part, the airplane can be flown without further major damage until inspected and repaired. However, the root of the problem is to understand the effects of service loads on the time required for development of discernible damage and rupture. There are two subproblems that will be dealt with separately — materials fatigue and structural design.

Materials Fatigue

1. Principal Problem. The basic mechanism of fatigue initiation or fatigue progression is not well understood; i.e., why some materials are much better than others and what can be done to improve fatigue performance of materials.

2. State of the Art. The current practice is to use experimental fatigue data on materials and then to average the data for applications to structures. There is such a large scatter in the test data that various statistical methods have been extensively employed for design. These methods result in excess structural weight.

3. Research and Development. Very little work is being done on the material fatigue problem. Generally, the procedure has been to experiment with alloying materials that will improve fatigue performance without understanding the reasons for success or failure.

Recommendation:

Establish a continuing and long-term program of research and development for achieving a better understanding of the basic mechanism of materials fatigue and for developing improved methods of fatigue analysis.

4. Suggested Government Role. The government should sponsor this research with the focal point being the NASA structures and materials organization. The actual research should be conducted through an organization such as a research institute.

Structural Design

1. Principal Problem. Using basic material fatigue data, methods of fatigue analysis and design must be developed that are much more accurate than present methods. Also, the method of handling crack propagation and fail-safety analysis must be improved to minimize structural weight penalties.

2. State of the Art. Probably no area in structural design has received as much attention in recent years as material fatigue. However, a great deal of this effort has been expended in testing actual production hardware from components to complete airframes. Although this has produced better designs through experience and weight saving, a basic research effort to understand the fatigue mechanism has not received sufficient emphasis.

Present methods for predicting airplane fatigue performance are inadequate. It is not uncommon to experience errors in analysis on the order of 200 to 1,000 percent.

3. Research and Development. Some fundamental work is being done in the United States and in Europe. However, other than the addition of weight to cover inaccuracies in analysis predictions, no significant improvement has resulted. This work should be conducted by a combined group of applied physics and applied mechanics people. The problem should be posed to a wide range of individuals in search of a workable analogy. With the advent of the computer, mathematical analyses have tended to be overworked to the exclusion of an understanding of the practical design application problem.

Recommendation:

a. Conduct research to improve the accuracy and provide the designer with knowledge of how to design satisfactory fatigue-resistant structure for minimum weight penalty. This work should involve physicists, materials specialists, and structural designers to formulate an improved theory of cumulative fatigue damage and improved methods for predicting crack propagation and fail-safe strength.

b. Conduct research on methods of micro-stress analysis, combined with a truly representative load history. Improved physical analogies are a suggested means of aiding in the stress analysis. Photoelasticity is such an analogy.

4. Suggested Government Role. The government should sponsor this work through NASA. Load history data that are necessary to the solution of the total fatigue design and fail-safety problem should be collected by NASA in conjunction with the airlines. Sufficient data should be obtained to define a sound statistical base for extrapolation to airplanes of the next decade.

Advanced Structural Concepts

1. Principal Problem. Significant improvements in structural weight can be achieved if new methods of construction and joining of materials can be achieved. Considerable weight penalties exist in present structures owing to the use of mechanical fasteners with their associated stress concentrations.

2. State of the Art. The mechanical fastener is used almost exclusively as the joining mechanism in today's aircraft primary structure. The associated stress concentrations and load transfer mechanism require intricate analysis techniques such as elastic load transfer analysis and photostress analysis to ensure satisfactory stress levels to prevent fatigue, stress corrosion, or static failure.

3. Research and Development. Industry is conducting research in this field by designing and testing new structural concepts, in some cases using new materials such as titanium, beryllium, and advanced composites. Manufacturers of adhesives should accelerate research on advanced adhesives to explore the total chemistry problem of adhesion and cohesion to ensure good and consistent properties over long periods of time when exposed to the expected airplane

environment including both low and elevated temperatures. The Air Force and industry should continue to press for this research.

Recommendation:

Initiate research on new ways of joining structures, such as adhesive bonding and diffusion bonding, in order to achieve improved structural capabilities. New and improved adhesive and matrix systems must be developed to permit reliable and efficient load transfer between different structural elements. This system must recognize the inspection problems associated with their use and must, of course, be competitive from a cost standpoint.

4. Suggested Government Role. Present government participation is centered with the Air Force in the form of research contracts with industry, primarily on advanced composites and beryllium. This activity should continue.

The Flight Vehicle: VTOL, V/STOL, and STOL System Development

1. Principal Problem. In viewing the total transportation system requirements for the next decade, it is apparent that the increasing overload of the system in the vicinity of major population centers can be reduced only by well-coordinated employment of all suitable modes of transport. One of the most promising modes that might contribute effectively to a solution is the V/STOL aircraft. Although the reliability and economy of such vehicles and their corresponding air and ground subsystems have not yet reached a level permitting them to play a major role in the nation's transportation system, they offer great flexibility when compared to fixed guideway systems, which are vulnerable to shifts in population and travel patterns. Because of the potential of V/STOL vehicles and because this potential has so far been virtually unfulfilled, increased effort on all aspects of V/STOL system development is warranted.

2. State of the Art.

Helicopters. Economically attractive aircraft are not presently in production. Derivatives of larger military transport helicopters could be made available that would be more economical, particularly over short ranges. New helicopters with a greater payload-range capability could be developed essentially within the existing state of the art.

V/STOL and STOL. The feasibility of several V/STOL and STOL configurations, other than the helicopter family, has been demonstrated, and economic analyses show these types to be potentially superior on the longer ranges, with the helicopter still superior on shorter routes. There is little or no operating experience on any of these new types, but there has been sufficient experimental work done on some configurations to justify additional development for both military and commercial operation.

Instrument landing systems. VTOL instrument landing systems are not available; current IFR approaches are made on the conventional shallow approach angle of fixed-wing systems.

Segregated air traffic control system. The National Airspace System, and planning for its future, does not provide for segregation of short-range traffic. The integration of VTOL and STOL traffic into the existing fixed-wing traffic frustrates the objectives of reducing air traffic congestion and reducing short-haul travel times.

Terminal planning and intermode relationships. If this mode is to make an effective contribution, its terminals and its interfaces with other modes must provide for a significant two-way traffic flow.

3. Research and Development. There is limited VTOL vehicle development, none of which meets commercial economic and operational standards. This development has been primarily experimental or military in nature and has been spread over many types of aircraft and propulsion. Limited IFR development work is being pursued; several modest programs are being conducted mostly for military applications. Only a few V/STOL air traffic control facilities are being planned and implemented. With regard to intermode connection capabilities, the CAB is establishing a schedule for investigating the possible granting of intercity VTOL operating rights within the Northeast Corridor. This is expected to motivate airlines to study the problems seriously in the very near future.

Recommendation:

Of primary importance in planning for VTOL, V/STOL, and STOL transportation systems is the need for research in the following fields.

a. Conduct a variety of vehicle-oriented research and development aimed at suppressing V/STOL noise. Accept-

ance criteria for noise analysis, consistent with the operating environment, should be developed. Research should be emphasized in the fields of control response, handling requirements, design margins, maneuver and stall margins, trades involving propulsive lift versus aerodynamic lift, and stability and control aspects of aerodynamic-propulsive force interaction. Additional research and development is needed to improve understanding of propulsion cycles, to better define pilot workload and display requirements, and to aerodynamically improve rotors and propellers, including stopping and stowing phases for rotors and propellers. Structural research and development is needed specifically directed toward the requirements of VTOL, V/STOL, and STOL aircraft, including increased fatigue life, improved prediction techniques for fatigue life, improved materials, reduced fatigue scatter factors, and improved manufacturing techniques. Further research and development is needed to improve propulsion cycles and power-weight ratios and to create lightweight power transmission systems consistent with the operating environment.

b. Develop instrument landing systems to permit steep gradient approaches for both VTOL and STOL aircraft under conditions consistent with the lowest prevailing weather minimums for fixed-wing aircraft (Category IIIC). The high frequency of such landings in a short-haul operation may dictate automatic landing systems.

c. Develop improved airspace utilization systems and, where necessary, segregated air traffic control systems, through simulation and operational experimentation.

d. Develop improved terminals and intermode connection capabilities on a basis compatible with other modes to attract and handle a significant traffic flow.

4. Suggested Government Role. The development of a total system concept and approach must be accomplished under the auspices of a central planning agency, such as the DOT, supported by the research of NASA, and the manufacturing and operating industries. Full use should be made of potentially applicable development work already accomplished for military use. Because a V/STOL transportation system becomes economically viable only when technical development, terminal planning, traffic control, and regulatory and operational plans are available concurrently, only the government can adequately plan and implement the total

program. The DOT would be the logical agency to have the responsibility, with NASA in a strong supporting role in research areas.

*The Propulsion System: The Engine**

Combustor Research

1. Principal Problem. Additional research effort is needed in the field of combustion design. The potential for improved efficiency is significant and the level of effort should be increased to be commensurate with research conducted in other fields directed toward improving airplane efficiency.

2. State of the Art. Gas-turbine combustor design today is based on fixed geometry mixing chambers where combustion is initiated and completed with a low-velocity axial flow by means of high recirculating air currents induced by pressure loss mixing. This produces a nonuniform stream and incomplete reaction products. Further, the concept requires a diffusion of air from the compressor to a fairly low combustor entrance Mach number in order to recover the pressure required for mixing in the combustor system.

3. Research and Development. Combustion work done by industry has been oriented to conventional problems related to improving temperature spread patterns, atomization, smoke reduction, and temperature limits of low Mach number combustion chambers.† Much of the combustion technology at higher Mach numbers has been related to the supersonic ramjet concept. As a result, a gap exists between low subsonic and high supersonic combustion research. By costly trial and error development,

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* Aircraft engine noise reduction at the source, attenuation through improved installation, operational procedures, and land-use practices were discussed by the committee during the study. However, it was considered appropriate for that discussion to be covered in the report of the ASEB Ad Hoc Committee on Aircraft Noise.

† It should be noted that there are currently flying commercial jet engines that have demonstrated significant and acceptable reductions in exhaust smoke.

there is a tendency by the industry to view combustion technology mainly as an art to be applied to a specific engine development. As a result, very little direction or money is available to explore adequately the innovations that present aerospace technology indicates are possible in a combustion system. The core of activity, therefore, must originate and be sponsored by the government with a contract to qualified industry for development, after the appropriate research within the government laboratories has been done to verify the concept.

Recommendation:

a. Seek further improvements in present gas-turbine combustor design concepts through the use of variable geometry primary zones and air atomization fuel injection. Both of these features have been explored on a limited basis in small vehicular gas-turbine applications, but considerable development remains before they can be considered in aircraft gas-turbine applications. The payoff is in proper mixture control over wide turndown ratios, thus maintaining complete combustion reaction and good mixing from takeoff through cruise operating conditions. This should materially reduce air pollution and reduce temperature gradients in the turbine.

b. Develop fluid dynamics control of the high Mach number flow from the compressor so that pressure recovery can be obtained locally in the combustor mixing jets. This would allow a higher convective cooling of the combustor chamber and would reduce the size of the internal ducting and pressure losses normally required for diffusing the total flow from the compressor.

c. Combine ramjet and scramjet principles in the gas-turbine combustor system. As pressures and temperatures of the cycle increase, it becomes more feasible to inject fuel into the compressor to achieve an isothermally compressed and premixed combustible mixture. Combustion may be initiated in the high subsonic flow and completed around aerodynamic flameholders (opposed jets, etc.) or in supersonic streams behind a standing shock system. Although somewhat advanced relative to present application, these schemes are generally feasible. The potential payoff for specific advanced gas-turbine propulsion systems should be elevated to identify research emphasis.

4. Suggested Government Role. Mainly, the role of the government should be to explore and establish the feasibility of combustion along the lines indicated and to encourage industrial participation in the development of these new systems.

Compressor Technology

1. Principal Problem. Current compressor technology is characterized by a need for a more detailed understanding of the flow phenomena inside a compressor—during steady-state operation, just before and at surge, under dynamic inflow conditions, and with respect to noise generation. In the next decade, it will be necessary to describe compressor performance much more acurately than at present and, at the same time, to reduce significantly the long development or redevelopment times for compressors. Increasingly unfavorable operating conditions for compressors and the fact that propulsion systems will be more closely integrated with airframes dictate the need for such improved capabilities. Overall system analysis will demand much more rapid turn-around times from the compressor designer.

2. State of the Art. Steady-state compressor performance prediction is based largely on previous similar designs and a number of empirical correlations. Detailed analytic techniques are in their infancy. Such techniques that are used are based largely on empirically determined factors. The determination of the surge line is for most steady-state operating conditions, including steady-state distorted inflow, a matter of empirical correlations. The behavior of compressors under dynamic inflow conditions is not understood at all. In fact, there are very little reliable detailed data available on the subject, and there is virtually no understanding of the interactions between steady-state and dynamic distortion. First steps—mostly outside the United States—have been taken in the direction of an understanding of noise generated by compressors; however, truly general analytic methods are still lacking for the most part.

3. Research and Development. A significant increase is required in the present level of research and development support on the problems described. Only fragmented attacks have been made on some aspects of the first three areas listed below, most of which were inspired as a result of information

gained on the F-111 program. Results of work on reduction of noise generation of fans and compressors indicate that much greater effort is required. Committee recommendations for the necessary efforts are described in the following paragraphs.

Recommendation:

a. Develop detailed analysis techniques, including the use of stations inside blade rows, for steady-state performance prediction. These techniques must, in particular, be brought to bear on off-design cases that currently are analyzed by the convenient but insufficiently powerful pitch-line stacking method. Detailed accounts must be made of viscous effects, particularly at hub and tip, of shock-boundary layer interactions, and of how these effects can be modified by variable geometry and boundary layer control. It would be a great benefit to all interested engineering organizations if detailed data could be published about a number of modern compressors with widely differing design characteristics (aspect ratio, stage loading, tip speed). These data could then be used by all researchers for testing new theories. The NACA five-stage compressor is too old for this purpose, and more importantly, it represents only one design philosophy. The new techniques should be used at an early time to develop compressors whose flow requirements can be more closely matched to those of supersonic inlets. In these attempts the role of supersonic compressors should not be overlooked.

b. Develop new analytic techniques for predicting compressor surge, both with steady-state and dynamic inflow conditions. The much better understanding attained in these studies also should be exploited to develop, if at all possible, a device that will warn when surge is imminent. Such a device would play an invaluable role in modern engine control systems.

c. Develop analytic tools that will predict the behavior of compressors under dynamic inflow conditions. It may be necessary to break the compressor down into separate stages. The technique would depend on the research described above to define when surge occurs.

d. Develop analytic methods to predict compressor and fan noise as a function of fundamental fluid flow parameters such as relative Mach number, angle of attack change, blade loading, and turbulence level of inflowing air. Of particular interest is an answer to the question of whether lack of noise generation is

inescapably associated with unfavorable effects such as lower efficiency and more weight.

e. Consider the establishment of a national experimental facility for turbomachinery noise research. If established, such a facility should in principle be similar to that established in England, but it should be open for research by both government and industry.

4. Suggested Government Role. The overall plan for research and development should come from NASA, but it should be much bolder than current NASA philosophy, including operation of such facilities as those suggested in item e above. Moreover, the government should clearly distinguish the difference between the general technology program and specific programs aimed at urgent military problems. Government, industry, and perhaps universities should all work on the problem. The latter may be able to make valuable contributions to new analytic techniques if significant data are available against which to test new theories.*

The Propulsion System: Installed Performance

1. Principal Problem. The prediction of installed propulsion system performance has become a major problem complicated by the introduction of high-bypass-ratio engines for subsonic airplanes, the need for an efficient supersonic transport, and the conflicting requirements of multimission military aircraft. Current experimental techniques for measurement and analysis of steady-state performance, both of scale models and full-scale systems, are underdeveloped. A sound insight into the usefulness of various proposed techniques is lacking. In addition, there is insufficient capability to predict whether dynamic problems will limit the operating envelope of the propulsion system or merely cause a performance deterioration. The very large sums of money involved in correcting any installed performance deficiencies make it highly desirable that the current state of the art be improved significantly.

2. State of the Art. Current wind-tunnel techniques are just starting to explore the use of powered airplane models

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* The success of this overall plan and the recommended research will be dependent on the vigor with which the recommendations in "The Propulsion System: Instrumentation and Controls" are pursued.

that more closely simulate real airplanes. Some testing has been done with turbo-powered nacelles, and some with propulsion systems producing propulsion jets, but having faired-over inlets. Very little work has been done with systems in which an ejector simulates the actual engine. No thorough systematic approach has been made to the simulation problem. Good data from different techniques are not generally available, and therefore it is difficult to say with any certainty which simulation techniques are good under particular conditions. Current methods of calculating in-flight thrust of engines are quite inaccurate for high-bypass-ratio engines. Some attempts are being made to come up with better precision, particularly by selecting as independent variables those propulsion system variables that will produce best overall accuracy, according to error analysis. The dynamic behavior of propulsion systems has been analyzed for some years with digital analog techniques, and much useful insight has been gained. However, almost invariably the components of the system are represented by lumped parameters, and this limits the applicability of the analyses. Little work has been done in calculating the performance degradation of the propulsion system because of dynamic effects, and the additional safety margins that are imposed in order to account for the dynamic effects. There is a serious possibility that supersonic inlets, compressors, and augmentors should be specifically designed to accept or produce minimum dynamic effects, rather than optimum efficiency or minimum weight. The lack of refined dynamic analysis techniques makes current industry studies of little value.

3. Research and Development. Various fragmented efforts are carried out by NASA, the military, and industry. While the scope of the problem is realized in the Air Force, not nearly enough is being done to improve the overall state of the art. A significant increase in support for research, test, and analysis is necessary as described below.

Recommendation:

a. Conduct a systematic experimental program to verify methods of predicting steady-state installed performance. The program should cover a number of typical problem cases such as subsonic transports in cruise, supersonic aircraft at high subsonic and various supersonic speeds, and a highly

integrated fighter aircraft in various flight regimes. For each of these cases all propulsion system simulation techniques should be compared to discover the strong and weak points of each technique. A generally applicable philosophy should be developed out of this program for correlating model and full-scale installed propulsion system performance. The first series of tests should be carried out with reasonably large models of engines (at least 5 or 6 in. in diameter). The problem of translating model data to full-scale data needs to be kept in mind at all times, and adequate methods should be defined as the insight to small-scale simulation problems improve. Later efforts should be addressed to reducing model size and to defining limitations for use.

b. Develop refinements in the analytic models used to handle dynamic problems. Not only should the components of the propulsion system be better described, but the airframe should be added to the model so that the overall engine and airplane system can be studied. Perform studies to evaluate the penalties on installed propulsion system performance caused by dynamic effects. Such studies should first assume such current practices as adding to the compressor surge margin and inlet stability margin; they then should calculate the economic incentive of using more refined control techniques. While inlet and compressor have specifically been mentioned, it should be understood that specific configurations or engines may have installed performance problems for other dynamic reasons and in other components. In general, it should be expected that the analytic models used to study operating envelope limitations (described above) would help to pinpoint such problem areas.

4. Suggested Government Role. NASA and the airframe industry should together attack the steady-state performance testing problem. Some NASA laboratories have the capability, but the urgent need for an improved technology should make it desirable to create closely cooperating NASA-industry teams for various subtasks. Initially, most testing should be carried out in the large government-owned wind tunnels.

For the dynamic analysis techniques, industry has ample capability, but an overall coordinated plan of attack is required. Since it may be expected that future military

design competitions will prescribe the dynamic analyses to be carried out, it would seem logical to let a military agency coordinate and guide this particular technology development, with commercial fallout. Ultimately it can be expected that some of the dynamic analyses will become requirements for certification of commercial airplanes. For that reason, the FAA should be kept informed of the developments and techniques.

The Propulsion System: Instrumentation and Controls

1. Principal Problem. Instrumentation and control systems on engines have seen little change since the introduction of jet engines. Even in research and development, instrumentation innovations have been rare, in sharp contrast to the sophisticated innovations that the space industry has produced. With continued development of improved instrumentation, control systems and monitoring systems could be developed for improved maintenance procedures and for compatibility with the general trend toward automatic controls. The complex performance requirements of military multimission aircraft and of the SST have made it imperative that the propulsion system be actively controlled to its optimum performance under widely different conditions. Moreover, a large payoff can be realized if engine health, or lack of it, can be quantitatively described so that maintenance can be carried out only when necessary.

2. State of the Art. Current engine instrumentation consists mostly of measuring engine rpm, pressures, and temperatures (but only in moderate- and low-temperature zones). These parameters are then used to imply certain basic conditions, such as turbine inlet temperature (TIT). Recently some attempts have been made to measure TIT directly and in a practical manner as well as to detect the onset of compressor surge.

In general, engine research instrumentation is old-fashioned compared with the sophisticated techniques used in space and ordnance research.

Most control systems are of the open-loop hydromechanical type. Some attempts are being made to evaluate fluidic systems, and these have met with a reasonable degree of success. Electronic controls seem far less developed in the United States than in England, where they have been

successful on the Britannia and will be used on the Concorde. The Concorde engine control system demonstrates clearly one desirable feature, namely, its capability to diagnose the system's own health.

On-condition maintenance promises a significant payoff, even for subsonic transports. However, a concerted effort to improve sensors and diagnostic techniques is lacking.

3. Research and Development. Essentially no instrumentation has been developed for jet engines, although there has been some developed for controls, particularly fluidic engine controls. On-line maintenance investigations are carried out by a few airlines, but the investigations are seriously handicapped by current instrumentation state of the art. With continued development of advanced instrumentation, control systems and monitoring systems could be developed for improved maintenance procedures and for compatibility with the general trend toward automatic controls.

Recommendation:

a. Develop new instrumentation sensors that are rugged, reliable, and fundamental to propulsion system control and health monitoring. In particular, effort should be made to find practical TIT sensors and/or sensors of turbine vane and blade temperatures. Also, a compressor surge warning sensor would provide a great payoff.

b. Develop for research purposes miniaturized probes and transducers for detailed study of the flow phenomena in inlets, compressors, burners, turbines, and nozzles. More sophisticated applications of well-known techniques should be evaluated actively (e.g., the application of Schlieren systems to compressor, turbine, and machinery research, miniaturized telemetry, and diagnostic acoustics).

c. Make a determined effort to develop propulsion system control technology. Systems should be developed and flown in actual service to establish reliability and practicality.

d. Develop a new concept for engine health monitoring and its relationship with engine maintenance, including new sensors, improved specific diagnostic techniques, and improved hardware to keep records of engine health data with a minimum of human participation.

4. Suggested Government Role. The agency most suited for the role of central coordinator and organizer is NASA, but emphasis must be placed on obtaining timely solutions.

Close liaison should be maintained with industry, the military, and the FAA so that new ideas can be applied with minimum delay.

The engine industry and NASA both should tackle the instrumentation problems. Significant advances in control technology require an overall national objective with parallel, competitive efforts. Close cooperation will be required between engine, control, and airframe manufacturers. Actual use in flight, e.g., military airplanes, seems an inescapable prerequisite for wide acceptance in commercial aviation.

The Propulsion System: Fuels

1. Principal Problems. The introduction of aircraft that are larger and in some cases possessed of higher performance than current aircraft suggests the need for improved fuels.

2. State of the Art. Fuels in use today are generally similar to or minor improvements of fuels in use for the past decade of civil jet operation.

3. Research and Development. The development of new fuels offers possibilities of improved efficiency, reduced weight, increased safety, and reduced air pollution, although no single new fuel will be likely to possess all of these improvements. Some of the new fuels may require the development of new engine cycles in order to realize fully the benefits to be obtained.

Recommendation:

a. Encourage research and development to achieve practical availability of new fuels providing for the best combination of efficiency, weight, safety, and pollution characteristics.

b. Encourage research and development of propulsion systems compatible with the characteristics of any promising new fuels developed.

4. Suggested Government Role. Continued support for and coordination of research and development efforts by government agencies is recommended. The current government-industry cooperation should be maintained.

Aeronautics and Space Engineering Board

Appendix I

Aeronautics and Space Engineering Board

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Appendix II

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